A Proposed New Storm Surge Scale[†]

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***Abstract*-The high storm surges of Hurricane Katrina (2005), Rita (2005), and Ike (2008) demonstrate that other forcing factors besides maximum sustained winds require attention. Indeed, the National Hurricane Center recently removed surge estimates from the Saffir-Simpson scale, since it does not incorporate storm size, bathymetry variation, translation speed, and other factors. This paper proposes a new scale which includes combined factors. An alternate scale based on Integrated Kinetic Energy (IKE) is also presented. Additionally, the eastward displacement of 5-ft and 10-ft surge inundation based on these combined factors is computed. The key concept is that coastal regions need to be defined by "bathymetry zones" which identify their vulnerability by shallow water proximity and the extent of the continental shelf. Other factors (such as storm size and speed) provide minor adjustment to surge estimates. This work has resulted in tables and plots which can theoretically be used in an operational setting, and also clarify surge forcing factors.**

I. INTRODUCTION

It is now well-recognized that the original Saffir-Simpson (SS) scale's relationship of storm surge based solely on intensity is not valid. The SS scale's intention was to estimate potential surge inundation and damage to property based on a hurricane's sustained wind speed. However, storm surge depends on intensity, storm size, bathymetry, storm speed, barometric pressure, and local topographical features. A combination of these factors results in large surge differences between hurricanes of comparable intensity, such as Category 4 Hurricane Charley's relatively minor surge inundation versus Category 3 Katrina's record surge. Indeed, the National Hurricane Center recently removed surge estimates from the SS scale, and renamed it the SS Hurricane Wind Scale, focusing solely on peak wind relationship to storm category.

It has also been proposed that Integrated Kinetic Energy (*IKE*) may provide a better correlation to storm surge than intensity. IKE is defined as:

$$IKE = \int_0^z \int_0^r \int_0^{2\pi} \frac{1}{2} \rho V^2(r) d\theta \, dr \, dz \qquad (1)$$

where ρ is air density, V is the tangential wind, z is height, r is radial distance from storm center, and θ is the azimuthal angle. It has been postulated that *IKE* incorporates wind structure, and therefore may relate to surge better.

A new scale will be presented which accounts for additional surge factors. A second scale using *IKE* will also be presented. Since the extent of surge inundation outside landfall regions is also important, eastward surge inundation using these factors has also been calculated. The key concept is that coastal regions need to be defined by "bathymetry zones" which identify their vulnerability by shallow water proximity and the extent of the continental shelf. Other factors (such as storm size and speed) provide minor adjustment to surge estimates. This work has resulted in tables and plots which can theoretically be used in an operational setting, and also clarify surge forcing factors. These results are based on hypothetical surge simulations using the Advanced CIRCulation (ADCIRC) hydrodynamic model.

II. GRID AND MODEL SETUP

A cross-section examination of different Atlantic and Gulf of Mexico coastal city bathymetries (Fig. 1, left side) demonstrates a wide variation of shallow water depth/slope and continental shelf location. Some locations, such as Gulfport, MS, are adjacent to very shallow water out to 100 miles, and therefore very vulnerable to storm surge. In contrast, Fort Lauderdale, FL, is near very deep water and would experience relatively minimal storm surge. In between is a wide variation of coastal bathymetries. We subjectively define six bathymetry classes to represent these variations (Fig. 1, right side): *very deep, deep, moderate, average, shallow, and extremely shallow.*

The ADCIRC grid (Fig. 2) is a rectangular area containing covering an oceanic region from 98-82^{o}W to 26-30^{o}N. Land covers the northern boundary. The land has a linear slope of 14/3200 which is 0 m at the shoreline and linearly increases to

[†] Work sponsored by NOAA with Grants NA060AR4600181 and NA050AR4601145, and through the Northern Gulf Institute funded by Grant NA06OAR4320264.

14 m at 2 miles in land. The land elevation remains constant at 14 m another 2 miles inland. The other boundaries are open water. The grid contains 28701 nodes and 54792 elements which are coarse away form the coast, then increases in resolution towards the coast. The highest resolution (where the hypothetical hurricanes make landfall) is in the central north boundary, with a grid spacing of $\Delta x \approx 90$-190 m and $\Delta y \approx 160$ m on the coast. Six grids are created which represent the bathymetry classes offshore.

The momentum fields are based on a variation of the Holland wind profile:

$$
\begin{aligned}
&p = p_c + [p_{env} - p_c] e^{-Ar^{-B}} \;; \\
&V_{mot} = \left[\frac{AB[p_{env} - p_c] e^{-Ar^{-B}}}{\rho r^B} \right]^{1/2} \;; \\
&A = R_{\max}^B \;; \\
&V_{\max\_mot} = \left(B/(\rho e) \right)^{1/2} \left(p_{env} - p_c \right)^{1/2}
\end{aligned}
\tag{2}
$$

where p_c is the central pressure, p_{env} is the environmental pressure, *e* is the natural logarithm, $R_{\max}$ is the radius of sustained maximum winds $V_{\max}$. *A* and *B* are scaling parameters which control the wind profile. It should be noted that our formulation includes the storm translation motion in *V* (denoted by the subscript *mot*).

A multitude of ADCIRC simulations are conducted based on different combinations of: 1) Category 1, 3, and 5 intensity ($V_{\max\_mot} =$ 85, 120, and 155 mph); 2) Translation speeds for slow (5 mph), average (10 mph), and fast (15 mph) storms; and 3) Size defined by radius of tropical storm-force winds (39 mph) for small (150 km), average (250 km) and large (350 km) storms. When combined with the 6 bathymetry classes, 162 simulations resulted. Based on climatology values, $R_{\max}$ was set to 22.5 km for Cat 1 and 3, and 15 km for Category 5. SS values for p_c are used. Winds are converted to u,v components, an inflow angle of 20 deg is assumed within 100 km, and 10 degrees otherwise. Based on these specifications, an algorithm iterates for *B*, and the wind is output to the ADCIRC grid based on Eq. 2. When the wind reaches a low threshold far from the storm center, it is set to zero.

III. SURGE RESULTS

A. Speed influence

We define a threshold of 1-ft peak surge difference between slow and fast storms to discern the influence of storm translation speed. Overall, 54% of slow storms have higher surge − the majority of these cases are Cat 5 and extremely shallow bathymetries. 15% have less surge, and 31% exhibit no difference. Hence, very slow moving intense hurricanes, and all slow hurricanes in very shallow water produce the largest surge events relative to average and fast-moving storms. Figure 3 (left side) shows that most slow Category 5 hurricanes produce surge differences of 3-10 feet in contrast to fast Cat 5s, with differences of at least 4 feet for very shallow bathymetry.

B. Size influence

Storm size sensitivity also exists (Figure 3, right side). Large Cat 1 and 3 linearly increase for decreasing bathymetry to 2-5 ft differences. Cat 5 is 6-8 feet more for large storms for most bathymetries. These results, along with Section IIIA findings, provide correction factors which can be used in a new surge scale, to be discussed next.

C. Proposed storm surge scale

The simulations clearly indicate that bathymetry is an equally distinguishing factor compared to intensity. Storm size and translation speed provide minor influences as well. By defining bathymetry zones of increasing susceptibility (Zones 1-5), one can estimate storm surge for average size and average speed Category 1-5 hurricanes (Fig. 4). This chart can be corrected

for size and translation speed when appropriate, as shown in Figure 4. This figure visibly shows why the old SS scale was insufficient. For example, the large upper-end Category 2 Hurricane Ike (2008) impacted Galveston, a Bathymetry Zone 4, with a peak surge of 15-20 feet in the Bolivar Peninsula area. Currently, we are defining all Bathymetry Zones in the Gulf of Mexico and Atlantic. The most vulnerable areas (Zone 5) appear to be the western Mississippi coast and adjacent Louisiana marsh, and the western Florida peninsula around the Tampa area. Note that this scale is consistent with Katrina's surge of 27 feet, and that in theory a surge up to 38 feet is possible for a large, slow-moving Category 5 in such regions.

D. Alternate surge scale based on Integrated Kinetic Energy(IKE)

By substituting the Holland wind profile (Eq. 2) into Eq. 1, an analytical solution for *IKE* is derived:

$$IKE = \frac{\pi[p_{env} - p_c]r_{env}}{B}\left\{Be^{-Ar_{env}^{-B}} - [Ar_{env}^{-B}]^{1/B}\,\Gamma\left(-\frac{1}{B}, Ar_{env}^{-B}\right)\right\} \quad (3)$$

where Γ is the lower incomplete gamma function, and z=1 m for simplicity. This equation was validated against numerical integration routines of Eq. 1. Since *IKE* automatically incorporates storm size, one would anticipate a useful relationship to storm surge. However, scatterplots (not shown) of *IKE* versus surge elevation show a positive trend, but contain overlaps that prove a 1:1 relationship is not possible. For example, a large Cat 3 hurricane and small Cat 5 hurricane have similar IKE magnitudes, but produce different peak surges. This is because wind stress plays an important role in surge as well.

It was then hypothesized that combining $V_{\max}$ and *IKE* may produce a more useful result. After a variety of scaling experiments, it was found that a nonlinear combination of $IKE^{0.5}$ and intensity produces a linearly increasing trend for all bathymetries (Fig. 5). This scale varies from 0 to $7\text{X}10^6$ $\text{kg}^{0.5}$ J. In other words, a 0-7 metric could be used to represent storm surge potential based on bathymetric zone. The general public need not know how the metric is computed, and there is precedence for using metrics in other scales. For example, users of the Richter scale do not know or care that it is a base-10 logarithmic scale obtained by calculating the logarithm of the combined horizontal amplitude of the largest displacement on a Wood-Anderson torsion seismometer. This scale offers some advantages over Fig. 4. It is not quantized like the SS scale, where a 5-knot intensity difference can result in a unit Category change. It also focuses more on storm structure instead of just $V_{\max}$, and storm size no longer needs to be considered separately like in Fig. 4. However, speed corrections are still required. The disadvantage is that the general public will have difficulty understanding *IKE* and would have to digest yet another scale. One could argue the SS scale could contain decimals as well, although currently in practice it does not. Therefore, Fig. 4 is more practical and accessible to the general public.

It needs to be emphasized that storm surge model forecasts should provide the primary storm surge guidance, since they capture local terrain effects and provide a better 2-D depiction of the pending surge event. Figures 4 and 5 also don't provide inundation contributions for wave setup, which is a minimal influence in shallow bathymetry but can be important for Zones 1-3 where waves break close to shore. Local tide corrections may also be needed, especially on the U.S. East Coast (Gulf Coast tide differences are only 1-2 ft). These proposed scales are intended to educate the general public on their regional storm surge vulnerability, and to provide a quick surge forecast if models are not available, or if a sudden track, intensity, or structure change has occurred in a hurricane situation.

E. Extent of storm surge inundation

It is unfortunate traditionally so much attention is focused on the peak storm surge. Significant inundation can occur far from the landfall region, especially on the eastern (western) side in the Northern (Southern) hemisphere. For example, Hurricane Ike caused surge elevations of 4-8 feet in eastern Louisiana and Mississippi. The extent of 5 and 10-ft inundation were quantified in the ADCIRC simulations for hurricanes of average size and speed (Fig. 6). As can be expected, shallow and (especially) very shallow bathymetries exhibit large eastern inundation values. Shallow bathymetry may have 5-ft (10-ft) inundation 80-90 miles (35-60 miles) east of the storm center. Very shallow bathymetry may have 5-ft (10-ft) inundation 250-300 miles (85-105 miles) east of the storm center. These numbers increase for large, slow hurricanes, where 5-ft inundation extends 16-30% further east, and 10-ft inundation extends 170-38% further east.

An encouraging result is that eastern inundation levels off after Cat 3 intensity. Intensity and structure forecasts have only modest skill, and typical 12-h track forecasts have an average error of 30 miles. Because this scale is relatively insensitive to short-term track and Cat 3-5 intensity errors, some surge predictability exists for regions east of the pending landfall.

REFERENCES

Available upon request.

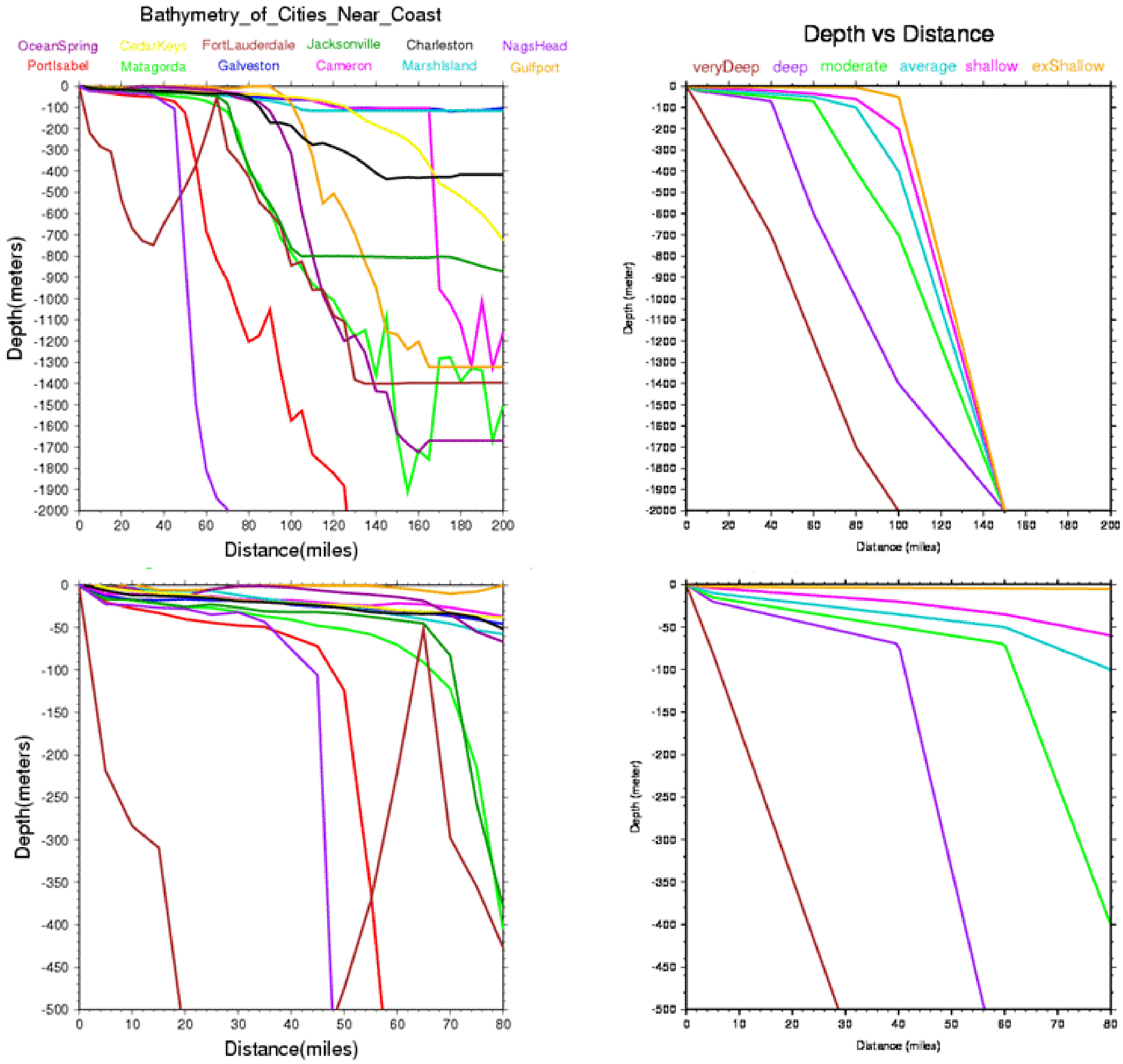

Figure 1. Bathymetry cross-sections for 10 coastal cities out to 200 miles (top left) and zoomed in to 80 miles (bottom left) that represent a spectrum of continental slopes. Six hypothetical bathymetries based on these cities are shown ranging from close deep water to a shallow continental slope for 200 miles (top right) and 80 miles (bottom right), defined as Very Deep, Deep, Moderate, Average, Shallow, and Extremely Shallow slopes.

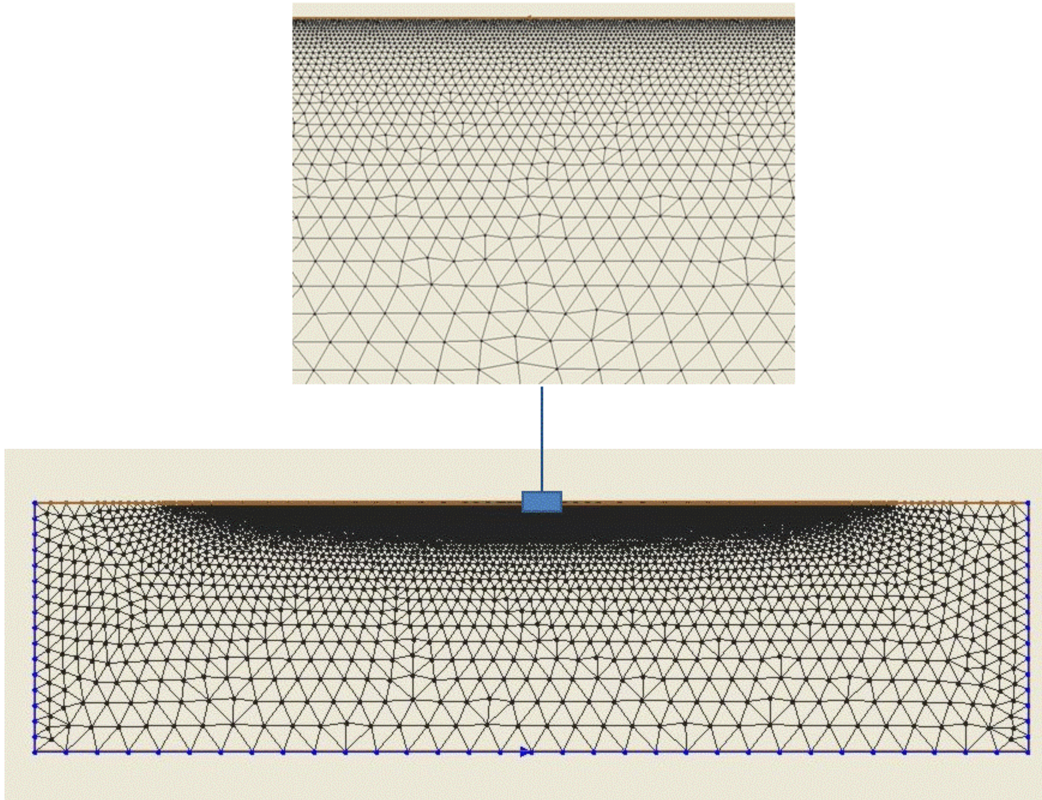

Figure 2. Grid used in ADCIRC simulations. Bottom figure is the full grid, and the zoomed-in portion of the blue highlight is shown in the top. The grid is ≈ 1527-km wide and 266-km north-south, with 28,701 nodes and 54,792 elements. The highest resolution is centered on the north edge with Δx ranging from 90 to 190 m and $\Delta y \approx 160$ m. Dry land extends inland 4 miles. The land height increases linearly from the coastline to 2 miles inland to 14 m, then remaining constant at 14 m.

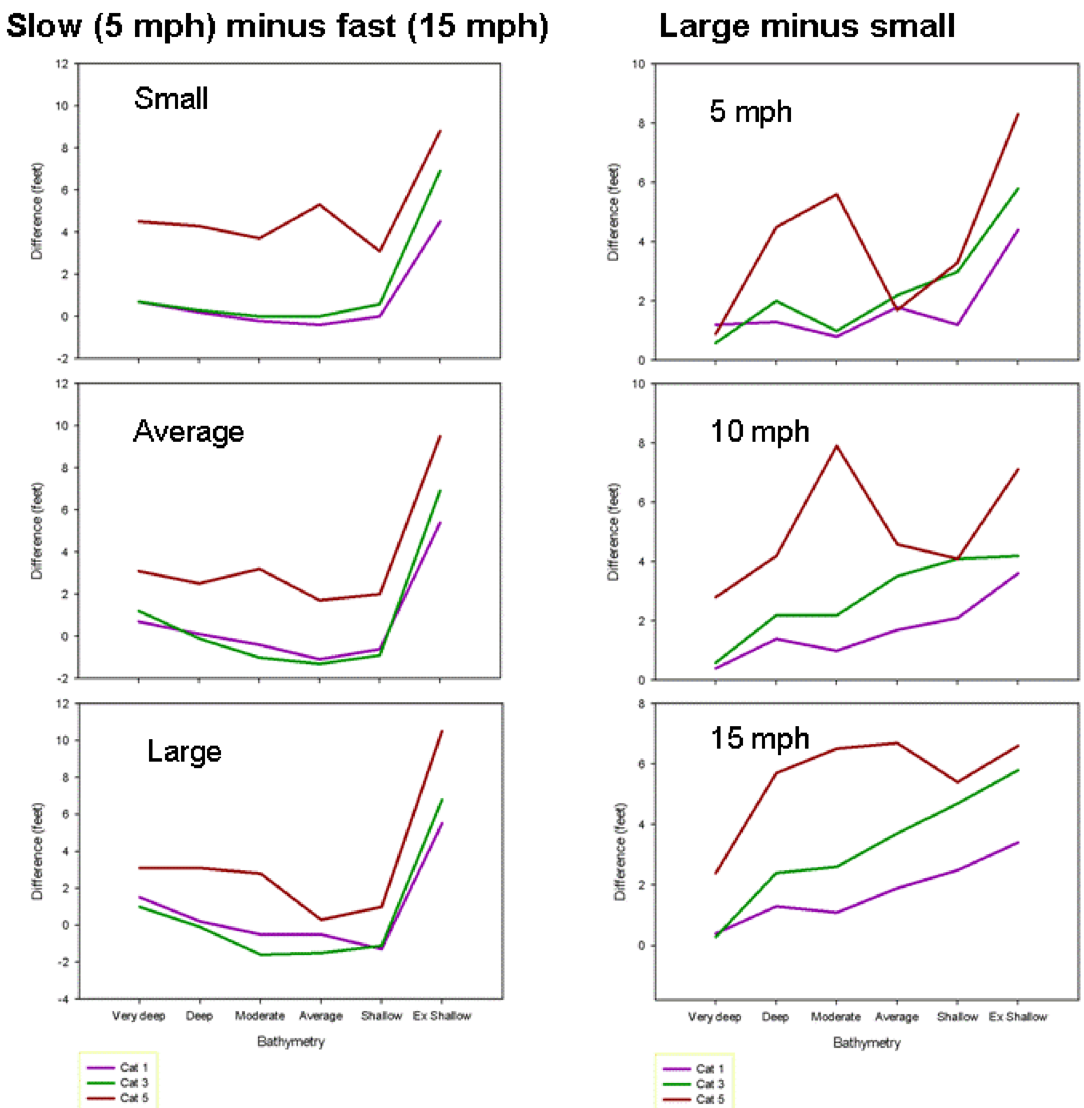

Figure 3. (Left side) Speed influence for small, average, and large hurricanes, computed by subtracting peak surge values for fast-moving from slow-moving storms. (Right side) Size influence, computed by large minus small peak storm surges, partitioned by translation speed.

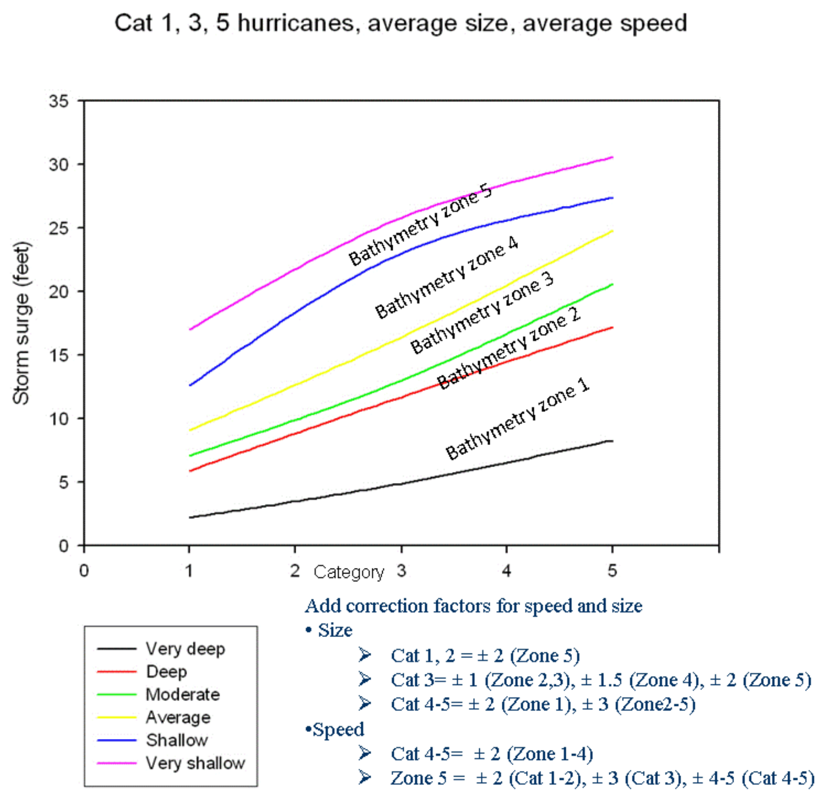

Figure 4. Proposed storm surge scale partitioned by bathymetry zones of increasing susceptibility (Zones 1-5) versus intensity. Relevant correction factors are shown under the figure.

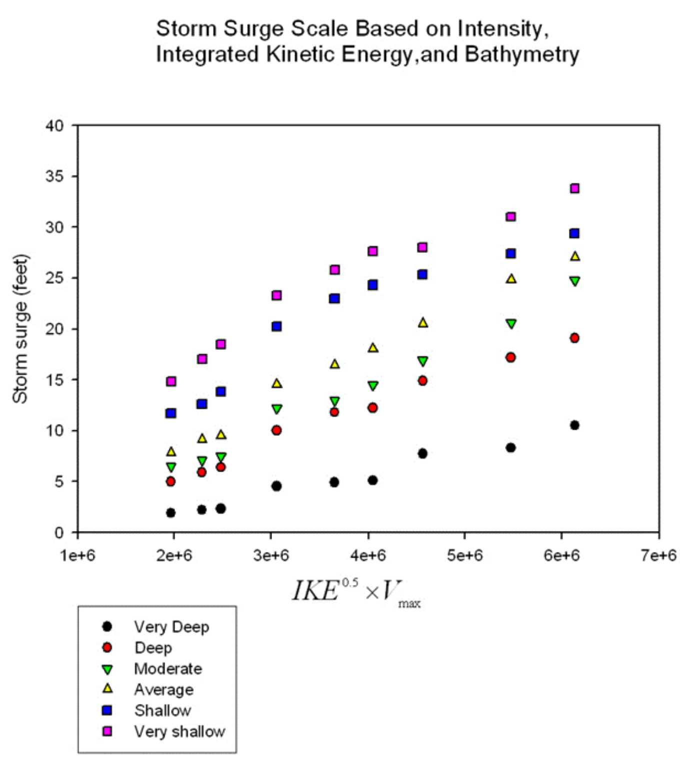

Figure 5. Nonlinear combination of *IKE*$^{0.5}$ and intensity versus surge for all bathymetries.

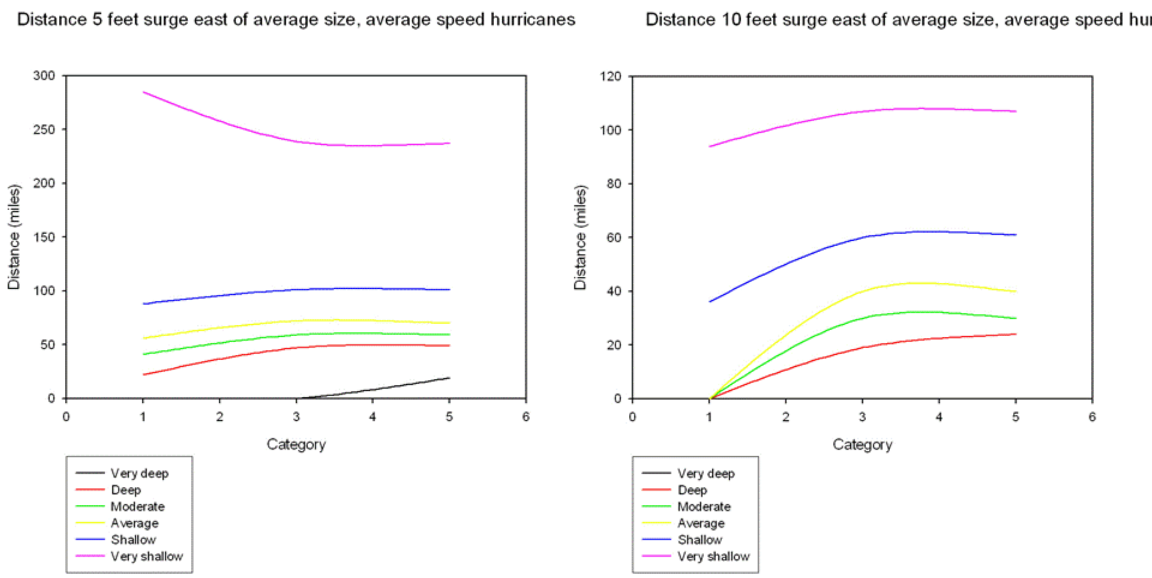

Figure 6. Distance (miles) of 5-ft and 10-ft inundation from storm center for average-speed, average-size hurricanes as a function of intensity and bathymetry classes.